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Translating citizen-generated air quality data into evidence for shaping policy

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The practice of participatory sensing for environment monitoring has rapidly evolved over the years. There has been a steady growth of citizen-based air quality monitoring projects that aim to build partnerships, knowledge-sharing platforms, awareness, and ultimately resilience to issues related to air quality. Whilst citizen science has reshaped air quality research by bringing a fresh perspective on democratizing science for the public good, there is little research about how citizen-generated data can be used for facilitating and improving evidence-based policymaking. To address the problem in a structured manner, we examine the existing literature related to citizen science, air quality, and policymaking to understand the existing gaps and opportunities. That is followed by a review of major grassroots and collaborative citizen science air quality monitoring initiatives in Asia, Africa, Europe, and Latin America. We explore the range of citizen science methods and applications to understand how they are creating opportunities for dialog between practitioners and policymakers, discuss the concerns about citizen-generated data, and see if the data is used for policy action. Finally, we propose a methodology for integrating data-based evidence into shaping policy. The methodology combines scientific evidence, participation, and deliberation to realize the full potential of citizen science in air quality monitoring.

Introduction

Air pollution is a global threat that negatively impacts public health and environmental sustainability (Brauer et al., 2016; Su et al., 2015). Many studies have associated particulate matter (PM) with millions of deaths across the globe (Pope and Dockery, 2006; Samet et al., 2000; WHO, 2014). According to a report by the World Health Organization (WHO), air pollution annually causes more than 2 million deaths in Southeast Asia, around 300,000 in the Americas, and around 500,000 in Europe (Taghizadeh-Hesary and Taghizadeh-Hesary, 2020). The effects are more clearly evidenced in urban areas, where people are exposed to pollutants like PM and nitrogen dioxide (NO_2). Emissions from industries, vehicles, incinerators, power plants, and agricultural practices are contributing to dangerous levels of air pollution.

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Given the serious nature of the problem, regulatory authorities like Environmental Protection Agencies (EPA) and policymakers in many countries have been responding appropriately by setting up large air quality monitoring networks and policies to reduce personal air pollution exposure (Arfire et al., 2016). These actions are mainly focused on deploying air quality monitoring sensors, acquiring data for policy formulation and implementation, and promoting behavioral changes. Traditional methods of air quality monitoring rely on fixed monitoring stations that are large and expensive. These monitors produce accurate data but are crude in terms of spatial and temporal resolution. Often cities with millions of people have only a few monitoring stations. This results in an inaccurate and biased representation of a city's air quality that could potentially affect the policies that are made to combat air pollution (Bales et al., 2012). To address this problem, Internet of Things (IoT) and low-cost sensing solutions have been widely used over the last few years for getting fine-grained air quality data (Camprodon et al., 2019; Chen et al., 2017; Kamel Boulos et al., 2011; S. Mahajan, 2018; Perera et al., 2014). Actions are aimed at creating campaigns where citizens are actively involved in monitoring air quality using low-cost sensors. Among all the initiatives, Citizen Science (CS) and participatory sensing strategies are considered promising approaches for generating new knowledge and information by providing greater geographical coverage at a reduced cost (Oltra et al., 2017). CS broadly refers to the practice where scientists and citizens work together to address a pressing issue by generating new knowledge and information (Bonney et al., 2009; Hecker et al., 2018). Within the air quality monitoring paradigm, CS projects are mainly focused on air quality monitoring using low-cost sensors. The data are used to complement the official monitoring frameworks, increasing spatial and temporal density (Schaefer et al., 2020).

Over the years, CS has evolved and is now recognized as a catalyst for evoking behavioral change by facilitating cooperation and coordination among multiple stakeholders (Sachit Mahajan et al., 2021; Van Brussel and Huyse, 2019). There has been significant growth in the number of CS air quality projects over the past few years. This growth can be attributed to: (i) conducting socially relevant research (Ballard et al., 2017), (ii) developing large datasets for better insights (Conrad and Hilchey, 2011), (iii) advancements in technology (Chen et al., 2017), and (iv) democratization of science (Sachit Mahajan et al., 2021; Pritchard and Gabrys, 2016). Instead of following a top-down approach for problem-solving, many CS projects have been following a bottom-up approach or a hybrid method for problem-solving (Jiang et al., 2018; Paul et al., 2018). This facilitates grassroots innovation and opens up possibilities for co-creating solutions that are responsive to local community interests (Helbing et al., 2021). The steady growth in the application of CS to monitor air quality has empowered citizens to contribute to air quality monitoring and understand the link between air pollution and health (Sachit Mahajan et al., 2020; Payne-Sturges et al., 2015). These practices are already bridging the gap between scientists and community members by creating a more inclusive and collaborative environment and strengthening the science–policy–society interface. Such collaborative environments can potentially open up spaces that promote interactions among key stakeholders, knowledge co-production, and sharing (Molinengo et al., 2021). It has also been found in many policy documents that CS can improve policy decision-making (Schade et al., 2021). However, these documents also discuss difficulties in transferring CS results in policy implementation often due to a lack of alignment between CS and policy agendas (Hecker et al., 2019). Furthermore, a major barrier is the translation of research output into useful information for decision-makers. Connelly et al. (2021) have already discussed how rethinking the concept of research translation can help address knowledge gaps at the science–policy interface. The question remains as to how the citizen-generated data can be used as evidence for shaping policy, or whether it should only be considered as a science tool. To understand how the existing literature links topics like air pollution, CS, and policymaking, we performed the bibliometric mapping of the current state of literature.

Bibliometric analysis. Bibliometric analysis is an efficient tool to map the literature in any domain of scientific knowledge. It looks into the existing literature and reveals the trends, networks, and also scientific gaps through text analysis (Zhang et al., 2019). To narrow down our search and do a more structural literature analysis, we used the keyword search query in the Web of Science[1] database to look for relevant literature. The search[2] was performed using the keywords "Citizen Science" AND "Air*" AND "Policy*". The search resulted in 72 documents that included articles, review articles, proceeding papers, book chapters, and editorials. We followed a two-step approach to analyze[3] the search results. First, we extracted frequently used keywords within the literature to understand word dynamics. It can be observed in Fig. 1 that "Air Quality" and "Air Pollution" are the two most frequently used keywords and their occurrence has gradually increased over the years. An interesting observation is related to the keyword "Citizen Science". It was only around the

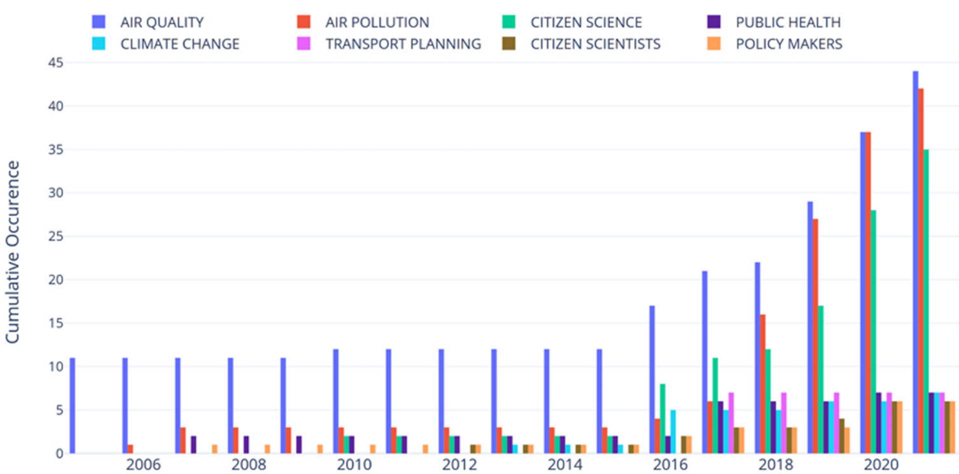

Fig. 1 Word dynamics graph. The graph shows eight most frequent keywords and their cumulative occurrence over time.

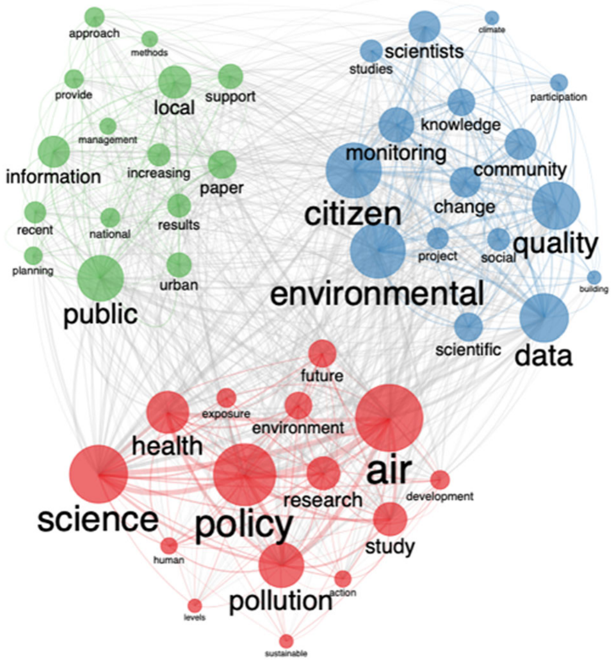

Fig. 2 Network visualization of frequently occurring terms. The figure shows three main clusters. Terms within the same cluster tend to be closely related to each other.

year 2015/2016 that it started showing an upward trend. This implies that the research discussing air quality and CS has quickly grown over the past 6 years. The keyword "Policy Makers" also appears in the literature but it has not been discussed as frequently as other terms like "Air Quality" and "Citizen Science". This implies that although air quality and CS research have grown over the years, the research bridging it with policymaking is still not widely explored.

The second step of the analysis used the co-occurrence method to find keywords that are discussed more frequently together and create a keyword co-occurrence network graph. Figure 2 shows the network graph in which highly occurring terms are the nodes and each node has at least two edges. Community detection within the network graph was performed using the Louvain method of community detection (Lu et al., 2015). It can be observed from Fig. 2 that there are three main clusters. Terms within the clusters tend to be closely related to each other.

One of the clusters shows strong links between health, science, policy, and air pollution, implying research focused on health impacts of air pollution and policies to mitigate the pollution exposure. The second cluster shows strong links between environmental monitoring, citizen data, and quality, implying that the research is mainly focusing on citizen participation in environmental monitoring, data sharing, and knowledge generation. There is another small cluster that looks into topics like public support, information management, among others. It can be observed from the network graph that there is a clear gap when it comes to research linking air pollution, policy, community engagement, and citizen-generated data. This reinforces the relevance of our study, which aims to fill the knowledge gap by exploring how CS air quality initiatives can connect researchers, citizen scientists, and decision-makers for knowledge sharing and data sharing, as well as shaping political decision making.

Motivation. Most air quality CS studies have objectives of scientific design, data collection, inclusion, collaboration, and knowledge sharing (English et al., 2018; Sachit Mahajan et al., 2020). However, it is imperative to understand how the data and results could be fed into policy debates (Oliver and Boaz, 2019; Van Brussel and Huyse, 2019). As discussed by Lepenies and Zakari (2021), there is a very limited meaningful connection between CS initiatives and official air quality policy formulation. Currently, solutions like citizen councils, joint projects promoting policy–citizen partnerships are underdeveloped and could be explored to promote meaningful participation of people in the policy-advisory process. This would ensure that the citizens are not merely data producers, but are directly contributing to better policies that would eventually affect them positively. As part of this paper, we examine how CS projects can foster a meaningful interplay between science, policy, and society, as well as how citizen-generated data can create new forms of public participation in decision-making. This paper also aims at steering the discussion on how inclusive and interpretable technology can enhance citizen participation, improve data quality and promote collective intelligence. We review current CS practices for air quality monitoring across Asia, Africa, Europe, and Latin America to comprehend the role of citizen-generated data in the larger landscape of scientific advice considered for decision making. The review explores how different projects across the regions co-create knowledge and evidence through a science–policy–society interface. We propose an integrated process for evidence production and use, that could be embedded within citizen sensing air quality monitoring initiatives. We expect that such a process will help realize the full potential of CS, thereby enabling better integration of citizen-generated data in shaping policies.

The promises of citizen sensing in air quality monitoring

Over the years, the concept of "citizen sensing" has gained a lot of attention. Citizen sensing is the practice of environmental monitoring using low-cost sensors and do-it-yourself (DIY) technologies (Pritchard and Gabrys, 2016). DIY sensing practices enable citizens to develop and use air quality monitoring tools and raise awareness for environmental or health issues (e.g., based on indoor air quality measurements). Recent activities also strive for new methods of social engagement and capacity building (Balestrini et al., 2021). As discussed by Schade et al. (2021), CS creates data that support setting policy goals and taking legal actions, while allowing citizens to participate in policymaking. The current discourse of citizen sensing in air quality monitoring highlights some major positive impacts related to participation and co-creation, diversity and openness, creating and using evidence, and citizen sensing at the Science–Policy–Society Interface. However, moving from DIY to do-it-together (DIT) poses additional challenges regarding the organization, coordination, and integration of social activities (Sachit Mahajan et al., 2021) (see also Box 1).

Participation and co-creation. The practice of participatory sensing in CS is often considered to be an effective strategy to promote community engagement in scientific processes. It not only contributes to scientific knowledge generation but also addresses some major societal issues (D'Hondt et al., 2013). Air quality has been a topic of concern in many developing and underdeveloped countries. Not only does it increase a country's disease burden but leads to economic costs. In the past, governments have implemented policies to combat air pollution, but their success and efficacy have been limited due to their top-down approach and lack of collaboration and coordination across key stakeholders (Holland, 1995). CS presents an opportunity to bridge the gap between key stakeholders by proposing a methodology that promotes the participation of citizens in monitoring

Box 1 | Options of CS initiatives to become part of the policy process

CS initiatives have different possibilities to gain political impact and momentum, including the following:

(1) Take evidence-based legal action, as some organizations aiming to protect the environment have done.
(2) Engage in joint projects with policy agencies or authorities, by forming public–civilian partnerships (rather than public–private partnerships, which form alliances of government and business). Note that public–private–civilian partnerships are conceivable as well.
(3) Form or interact with citizen councils, which are increasingly consulted by parliaments and other political institutions to address complex issues concerning civil society.
(4) Build and use platforms promoting collective intelligence, as some digital democracy initiatives have suggested and done.

The following sections of this paper will mainly focus on option (2).

their environment using open-source digital solutions. (Commodore et al., 2017). The key idea is to create an environment in which citizens can measure, analyze and understand patterns in the air quality (Goldman et al., 2009). Co-creation on the other hand promotes people-centered innovation and needs the full involvement of citizen scientists in the conduct and governance of CS projects (Froeling et al., 2021). Implementing the principles of co-creation in participatory research accommodates and facilitates the engagement and involvement of multiple stakeholders in all phases of the research process. Citizens and researchers work together in defining the key research questions related to air quality and co-create solutions that have a significant societal impact (Gabrys et al., 2016; Hecker et al., 2018; Sachit Mahajan et al., 2021). Co-creation promotes an open and creative process that allows for meaningful interactions and better utilization of products and resources (Greenhalgh et al., 2016; Ind and Coates, 2013).

Despite these benefits, combining participatory sensing with co-creation comes with some complex challenges. While such co-creation principles promote a decentralized approach that distributes power equally to all stakeholders, at the same time it can lead to uncertainties due to the lack of predetermined data collection and analysis plans (van Dijk-de Vries et al., 2020). Successful co-creation is, therefore, a complex combination of factors, such as communication, outreach, inclusive environments, and deliberative consultation. It has been observed that several community-led air quality monitoring projects (Camprodon et al., 2019; Gabrys et al., 2016; Gutiérrez et al., 2017; Sachit Mahajan et al., 2021) have successfully implemented the principles of co-creation thereby generating valuable societal and scientific impact. These studies highlight how citizens can proactively get involved in the co-creation of scientific knowledge.

Diversity and openness. CS programs across different disciplines have enjoyed huge growth over the past few years as they can provide benefits to the participants as well as their communities (Davies et al., 2011). One of the widely discussed topics within these CS programs is understanding whether the benefits are equally accessible to all sections of society or limited to the participant group (Guerrini et al., 2021). However, we want to point out that sometimes the CS study design is affected by the funding body's requirements, the deliverables, and the timeline. This can lead to issues like working with predetermined citizen groups that benefit the research project and deliverables but do not focus on complete demographic and geographic representation. We call this type of participation "cosmetic participation", where the benefits are limited due to underrepresentation of the community. Not only does this exacerbate inequalities, but also widens the gap between privileged and underprivileged sections of the community.

To approach CS with an environmental justice lens, it is important to recognize that certain sections of the community are more severely impacted by environmental degradation than others. While designing participatory sensing studies, it is imperative to create an inclusive environment that promotes representation from all sections of the society irrespective of their social status, gender, religious beliefs, literacy level, or age. As shown in the case of the AirBox project in Taiwan (Sachit Mahajan et al., 2021), researchers and community members worked together to create a nationwide air quality monitoring system that included everyone, from researchers to citizens, and from school students to decision-makers. The result was a successful citizen sensing initiative that helped in knowledge sharing, capacity building, and instilling change at the grassroots level. Similarly, the Citizen Sense (Gabrys et al., 2016) project in the UK worked with communities from Southeast London which is one of the highly polluted regions of London. The research team worked together with the community members, local councils, schools, museums, and local businesses to facilitate and organize new ways of environmental engagement. There are several other citizen-sensing initiatives like D-NOSES (Arias et al., 2018) that monitor odor pollution and follow an inclusive engagement strategy by bringing together people who share a common issue of odor pollution in their communities. Looking at the engagement models of all these projects, a key take-away message is to ensure that the engagement plan is defined from the outset of a CS project. Citizen sensing projects should acknowledge the concerns of affected communities while shaping their research questions. The engagement should not be limited to the start of the project, but it should be maintained continuously from the initiation of the project to its completion.

Creating and using evidence. The topic of citizen-generated data has been a highly contested and complex arena. Fritz et al. (2019) have already discussed how such data can be an important source of information for policymaking. There are several other benefits like an increase in the number of datasets for supporting data-informed decision-making as well as an increase in citizen engagement and interest in policy (Schade et al., 2021). However, there are many challenges related to data quality that exist at multiple levels. It has been often observed that the data requirements of CS projects don't always match the requirements of policymakers due to very specific project goals (Balázs et al., 2021). Citizen-generated data is often questioned and challenged by scientists and policymakers (Kosmala et al., 2016). CS projects sometimes follow complicated data collection protocols. The complication comes due to the nature of data and the technical knowledge that is needed to use data collection devices or instruments. Such complicated protocols can sometimes have a negative impact as the participants lose motivation and the sense of fun while doing data collection (Hochachka et al., 2012). Using black-box technologies and algorithms also add to these challenges. One way to address such challenges would be to use open-source tools and technologies (Sachit Mahajan and Martinez, 2020; Silva, 2013) that are well documented and easy to understand. Another strategy is to use more intuitive data collection practices that are engaging and compatible with the skills of the citizen scientist.

Different stakeholders have different ways of defining data quality. When it comes to air quality data, a lot of focus has been on quality assurance and quality control techniques. Official guidelines are there to make sure that the data generated is meaningful and is obtained by using the standard scientific methods (von Lehmden and Nelson, 1977). To further build trust between the regulatory monitoring bodies and citizen scientists, a lot of CS projects are following a three-way approach to address the issues of data quality and reliability. This includes sensor colocation to understand inter-unit variability, sensor colocation with reference instruments to perform calibration (Sachit Mahajan and Kumar, 2020; Zimmerman et al., 2018), and open data repositories to reuse the data and reproduce the results (Chen et al., 2017; Luftdaten, 2021). While participatory sensing has become a valuable source of data and information for citizens, researchers, and policymakers, the adoption of actual citizen-generated data in policy development is still slow. As argued by Veiga et al. (2017), a data user's perspective is important when discussing data quality and fitness for use. To increase the value of citizen-generated data and use it formally as evidence for shaping policy, it is important that all stakeholders co-develop the research agendas, the data quality standards, and clearly outline how the data would feed into the decision-making process. This will not only provide clarity to the citizen scientists about how their data would be used but also help researchers in creating tangible research impact.

Citizen sensing at science–policy–society interface. The notion of a science–policy interface that engages only experts and policymakers has become outdated (Liberatore, 2001). To solve complex challenges like climate change, air pollution, etc., the focus has shifted towards creating interactions between science and society to maintain a balance between scientific rigor, societal relevance, and political legitimacy. The official experts are no longer the only knowledge holders, but the social actors like community members, environment enthusiasts, citizen scientists, etc., are also actively participating in knowledge production and sharing. It has been observed that CS projects can produce relevant results; improve knowledge exchange between scientists, citizens, and policymakers, and have a positive impact on the science–policy–society interface (Kenens et al., 2020; Sachit Mahajan et al., 2021; Van Brussel and Huyse, 2019). As discussed in the OECD handbook (Gramberger, 2001), strengthening the government–citizen relationships can improve the quality of policies, promote transparency and accountability, and strengthen public trust in government. Several initiatives have been started by governments around the world to promote citizen participation in the policy process, for example, *VTaiwan*, which is an online–offline platform bringing multiple stakeholders together and helping policymakers make decisions with a greater degree of legitimacy (Schubach, 2018). The Government of the Netherlands[4] is also using a variety of forums to promote citizen engagement and find new ways for citizens and decision-makers to work together.

Despite these developments, the role of the wider public in participation and deliberation on key policies related to air quality has been limited.

Insights from geographical perspectives

Here, we discuss some of the major CS air quality monitoring projects across different regions to get insights into how these projects engage citizens, translate data into evidence, and create opportunities for dialog with decision-makers.

The search criteria for selecting the projects were based on the key concepts mentioned in the section "The promises of citizen sensing in air quality monitoring". We looked for the projects that followed a clear methodology for participation and co-creation, facilitated engagement and knowledge exchange, and highlighted the outcome of CS initiatives. In addition to studying the projects that appeared in research articles, we also searched blogs, forums, and websites for relevant and well-documented projects. The search resulted in 25 projects across different geographical locations that provided clear information about organization, methodology, and outputs. Based on the geographic location of the projects, we examined how they are formulated, how they are implemented, and what the outcome is.

Asia. Table 1 summarizes some key citizen-based air quality monitoring initiatives across Asia. Asian countries, especially East Asian countries like Taiwan, South Korea, and Japan, have witnessed the establishment of large-scale volunteer-based environmental sensing networks. One of those initiatives called the Location Aware Sensing System (LASS) in Taiwan has successfully mobilized the volunteer community in monitoring air quality across Taiwan using AirBox devices (Chen et al., 2017). LASS is promoting civic tech through a low-cost, bottom-up process that allows the public to create a comprehensive environmental sensing network system. At present, LASS has deployed more than 12,000 AirBox devices in Taiwan and the data is used for creating tools for digital assistance (Liou et al., 2020; Sachit Mahajan et al., 2018) and complementing the monitoring network of the Environmental Protection Agency (EPA). The project has significantly contributed towards promoting air pollution awareness, as well as urging citizens to actively monitor the government's air quality policies. AirBox has been recognized as a valuable smart city project and has also supported the government to develop the 'Civil IoT' initiative to develop and enhance the IoT ecosystem. AirBox project uses several co-creation activities like workshops, citizen forums, developer conferences, etc., to co-create monitoring scenarios and improve sensor design (Sachit Mahajan et al., 2021). Motivated by the effectiveness of Taiwan's AirBox program on environmental education and monitoring, South Korea's Gyeongsangnamdo Office of Education introduced AirBox in 2017 (Lee, 2019). The data has been widely used for creating awareness applications. A detailed plan put forth by the Gyeongsangnamdo Office of Education is focusing on "From local policy, change national policy". In Japan, Safecast is promoting participatory sensing and open information by supporting independent third-party monitoring (Brown et al., 2016). Safecast has mainly contributed to radiation monitoring in Japan, but recently they have developed AirNote sensors to monitor air quality. Safecast regularly collaborates informally with local and regional institutions in Japan and across the world and supports agenda-setting for international action. Data provided by Safecast has been recognized by policymakers at multiple levels, thus facilitating dialog between citizen scientists, researchers, and decision-makers (Brown et al., 2016). India, Pakistan, and Thailand are some of the most polluted countries, not only in Asia but in the entire world (Asia, 2021). Lack of government infrastructure and systems to monitor air quality has led to the deterioration of the air quality standards. There have been a limited number of citizen sensing initiatives that are trying to promote civic tech. In Thailand, the DustBoy (Supasri and Sampattagul, 2019) team is working with the local communities and councils to create monitoring networks to create awareness among the people. They use several co-creation activities like

Table 1 Summary of key citizen-based air quality monitoring projects in Asia.

Project	Aim of the project	Location	Initiators	Community tasks	Approach to data	Science–policy–society interface
AirBox (Chen et al., 2017)	To crowdsource air quality data for promoting behavioral change and improving environmental governance.	Taiwan	Academia, maker groups, local government	Monitoring site selection, sensor installation, monitoring pollution episodes	Open data policy to create more democratic digital solutions. Data is validated by comparing it with data from EPA monitors.	Inspiring the local government to develop policies for creating IoT air pollution monitoring networks. Assisting in the implementation of smart city policies.
DustBoy (Supasri and Sampattagul, 2019)	To expand the air quality monitoring network in Thailand.	Thailand	Academia, citizens, non-profit organizations, local government	Crowdsourcing data	Data streams are validated using a data model. Data is used to create early warning systems with the potential to change policies related to air quality.	Pressurizing the government to create action plans to reduce air pollution. Initiating policy discussions.
AirBox South Korea (Lee, 2019)	To develop a crowdsourcing system that provides citizens with environmental data and enriches air quality governance.	South Korea	Local government, researchers, and citizens	Sensor installation, monitoring air pollution incidents	Validated data is used for raising awareness and creating education programs.	Complementing environmental education in schools.
Respirer Living Sciences (Science, 2020)	To understand the use of air quality sensing solutions for policy and government use.	India	A startup company, academia, and non-profit organization	Sensor installation at pollution hotspots	Sensor data is scientifically evaluated with reference instruments.	Helping bridge the information gap. Data is used to support policy discussions.
PakAirQuality (Shi et al., 2020)	To raise environmental awareness and promote behavioral change.	Pakistan	Citizens, non-profit organization, a startup company	Sensor installation, crowdsourcing data	Data is mainly used for raising awareness about air pollution.	Promoting environmental awareness by collaborating with city councils and NGOs.
Safecast (Safecast, 2021)	To develop a CS-based air quality monitoring framework that fosters open processes of research co-creation and environmental action.	Japan, with limited presence in other parts of the world	Non-profit organizations, citizens, start-up company	Crowdsourcing air quality data	Portals allowing access to open data without licensing restrictions.	Advocating for data transparency and 'pro data' policies. Safecast data has been recognized by policymakers at multiple levels.

citizen workshops and online forums to co-create sensor deployment scenarios. The sensor data has been used to initiate a dialog with the decision-makers regarding air pollution monitoring infrastructure. Research groups and non-profit organizations are collaborating to address the air pollution problem in India. Respirer Living Sciences (Science, 2020) has been deploying Atmos sensors to monitor air pollution and other environmental parameters in twenty cities in India. The involvement of citizens in this project is limited as compared to other projects in other Asian countries, but it has the potential to become a large-scale movement where citizens would have an important part to play. In Pakistan, some local organizations have been using a commercial product called AirVisual (Shi et al., 2020) to raise citizen awareness of actual air pollution in the places they work and live, and thus contribute to a better air quality index (AQI) and promote positive changes in behavior. Although such practices are promoting change and awareness, the change achieved on the ground is very limited. Relying on commercial sensors brings more challenges related to data access and transparency, and therefore limits the engagement potential. Other reasons for limited impact could be technology-related barriers that hinder the engagement and motivation of citizens to participate in the CS project (Asingizwe et al., 2020). Such issues may discourage citizens from participating and reduce the impact of the CS project as a whole.

Despite all these initiatives, the application of citizen-generated data to policymaking has been limited. Taiwan and Japan have made some progress by using data generated by grassroots movements and traditional data for policy discussions, but there is still a lack of proper methodology to translate the data into information that can be used by policymakers for decision making.

Africa. CS practices in air quality monitoring in African countries are relatively new but they are already encouraging community engagement for addressing societal challenges. Air pollution is a major area of concern for researchers and policymakers and is taking a serious toll on human health and the economy in many countries in Africa. This can be attributed to an increase in industrial activities, environmental factors like dust storms, and the overuse of wood for cooking purposes. Based on a report (Yiu, 2019), only 7 out of 54 African countries have a real-time air quality monitoring framework. To improve the air quality monitoring infrastructures and raise awareness, many non-profit organizations, citizens, and research groups are working together. Table 2 summarises some of the citizen-based air quality monitoring initiatives across Africa. In Nairobi, Open Seneca (OpenSeneca, 2019) is working with maker groups, university students, and residents to monitor transport-related air pollution. It regularly collaborates with the maker community to co-create research design and get feedback and inputs regarding the sensor design. The data is used to raise awareness and influence urban planning and legislation. Grassroots initiatives like OpenAQ (OpenAQ, 2021), sensors.Africa (Sensors.Africa, 2021) and Open Cities Lab (OCL, 2019) are operating in different regions across the African continent to address air pollution at neighborhood levels and within marginalized communities. These projects involve local communities by organizing workshops that promote knowledge co-creation and sharing. The primary focus of these initiatives is knowledge sharing with multiple stakeholders and creating air quality datasets for awareness purposes. These projects are also advocating the creation of citizen sensing networks to supplement regulatory monitoring systems and assist in finding democratic solutions to combat environmental injustice. With growing CS initiatives across Africa, there is a potential to connect the citizen-generated data to evidence for environmental justice, social innovation, and decision making. Although the current CS initiatives are already reinforcing environmental governance, there is still a lack of infrastructure for engagement that allows formal institutions to interact with CS discourses and data. Based on a report (Association, 2016) that looked into top barriers to CS in Africa, limited access to relevant technology and lack of appreciation from policymakers are some of the key barriers to CS. To strengthen CS in Africa, it is vital to improve the technology used in CS projects in terms of relevance and accessibility and to raise awareness and understanding of CS among policymakers.

Europe. Over the past few years, citizen-based air quality monitoring projects have increased in Europe. Driven by the sense of responsibility and awareness, community groups have joined hands with maker groups, research institutes, and other key stakeholders to monitor air quality and contribute to knowledge generation and sharing. Table 3 summarizes some of the key citizen-based air quality monitoring initiatives across Europe. Most of the initiatives follow a collaborative approach that mobilizes grassroots and facilitates key stakeholder interaction to find efficient and sustainable environmental monitoring solutions (Bales et al., 2012; Kosmidis et al., 2018). The CS approach followed in the majority of studies (Brussels, 2021; Camprodon et al., 2019; Sachit Mahajan et al., 2021; Van Oudheusden and Abe, 2021) adhere to good scientific standards, data accessibility, and quality assurance. The crowdsourced data is used to create large air quality datasets and applications that complement the official air quality monitoring systems as well as stimulate environmental awareness and behavioral change. Projects like AirKit (Sachit Mahajan et al., 2021) have emphasized how the social aspects of IoT-based air quality monitoring can be a crucial component of technological innovation. It allows the citizens to use data stories for communicating data and proposing air quality interventions. A narrative approach of storytelling is often used to integrate sensor data with local knowledge to increase the impact. Some other community-driven programs like DataONE (DataOne, 2021) have been instrumental in providing access to the earth and environmental data. The initiative has special interest groups that focus on CS and policy.

Different projects across Europe have used a variety of co-creation activities. For example, hackAir project used workshops to collaborate with the intended users to co-create different components of the digital platform. Similarly, AirKit project used knowledge co-creation activities like community walks to find pollution hotspots as well as co-design pollution monitoring scenarios.

To understand the policy impact, we looked at the potential scenarios in which the crowdsourced data would contribute to policy debate. We found that there was a gap between the intended policy contributions and the realized ones. In most of the cases, there was a provision for communicating data to the decision-makers in form of a report, publication, etc. However, only in a few cases, like the Curious Noses (CurieuzeNeuzen, 2018) project in Belgium, the data was used for shaping policy. The project advocated for adding the issue of air pollution to the policy agenda and used the citizen data to highlight the exceedance of acceptable air quality standards. The 2030 Flemish Air Policy Plan[5] recognizes the exceedance of air quality standards.

Latin America. Poor air quality is one of the major environmental risks for health in Latin America (Apte et al., 2015; Bell et al., 2006) which affects the most vulnerable population as

Table 2 Summary of key citizen-based air quality monitoring projects in Africa.

Project	Aim of the project	Location	Initiators	Community tasks	Approach to data	Science-policy-society interface
Open-Seneca (OpenSeneca, 2019)	To empower citizens with air pollution data to raise awareness, promote behavioral change, and inform policymakers on environmental issues.	Kenya	Academia, research institutes, maker groups, non-profit organizations	Crowdsourcing air quality data	Validated data is used to promote behavioral change and inform decision-makers about air pollution issues.	Educating citizens to build air pollution sensors for monitoring transport-related pollution. Advocating for better urban planning and legislation.
Open Cities Lab (OCL, 2019)	To address the air pollution issue within marginalized communities.	South Africa	Non-profit organization	Crowdsourcing and interpreting data	Data is used to understand air quality challenges in poor residential areas.	Facilitating multi-stakeholder interaction and discussion on hyperlocal air pollution issues.
sensorsAfrica (Sensors.Africa, 2021)	To work with neighborhood communities to monitor air pollution.	Kenya, Nigeria, South Africa, Tanzania	Civic technology initiative, community members	Crowdsourcing air quality data using stationary sensors	Data is used to create responsive locally driven strategies.	Facilitating interaction between the community, local policymakers, and researchers. Advocating for action against environmental injustice.
OpenAQ (OpenAQ, 2021)	To empower communities around the world to clean their air by harmonizing, sharing, and using open air quality data.	Angola, Ethiopia, South Africa, Kenya, Nigeria, Ghana	A non-profit organization, citizens	Crowdsourcing air quality data	Open data platform to share data with multiple stakeholders.	Bridging the gap between science and policy. Advocating for open data to fight air inequality.
GHAir (Sewor et al., 2021)	To bridge air pollution data gaps in Ghana.	Ghana	Researchers, community members	Crowdsourcing air quality data	Data is used to provide real-time air quality information to promote behavioral change.	Opening up a dialog between citizens, researchers, and decision-makers. Influencing air pollution control policies.

Table 3 Summary of key citizen-based air quality monitoring projects in Europe.

Project	Aim of the project	Location	Initiators	Community Tasks	Approach to Data	Science-Policy-Society Interface
CitiSense (Kobernus et al., 2015)	To develop Citizens' Observatories that focus on the empowerment of citizens to influence their community policy and decision-making.	Multiple European cities	Academia, research institutes	Crowdsourcing air quality data, contributing with their subjective perception of air quality and other personal observations	Data is used for applications that empower citizens to contribute to environmental governance, facilitating communication between communities and policymakers.	Supporting communities and influencing policy priorities. Understanding the local policy context, possibility for change, and potential barriers to it.
hackAIR (Kosmidis et al., 2018)	To develop open platforms for enabling citizens to monitor air quality.	Multiple European cities	Research institutes, public health organizations	Crowdsourcing air quality data, co-creation of monitoring scenarios	Data validation with official networks. Open data platform to share data with multiple stakeholders.	Strengthening citizens' voices and bridging the gap between citizens, scientists, and decision-makers.
CuriousNoses (CurieuzeNeuzen, 2018)	To raise environmental awareness and promote behavior change.	Belgium	Academia, citizens, local governing bodies, designers	Crowdsourcing air quality data	Citizens collect the data which is validated by experts.	Multiple stakeholder collaboration to create policy-relevant data. Advocating for putting the topic of air quality on the national political agenda.
Innovation Program for Environmental Monitoring (Wesseling et al., 2019)	To develop a crowdsourcing system that provides communities with detailed environmental data, enriching the Dutch environmental monitoring network.	Netherlands	Research institute	Crowdsourcing air quality data	Crowdsourced data is used for developing modeling and assimilation techniques for using uncertain sensor data into air pollution models.	Supporting knowledge co-creation and sharing by the development of sensor data portal. Facilitating discussions about citizen involvement and sensor data quality.
Smart Citizen Kit (Camprodon et al., 2019)	To develop a crowdsensing system to generate real-time data and awareness about pollution in	Multiple European cities	Academia, research institutes, maker groups	Crowdsourcing air quality data	Data is integrated with open-source tools for knowledge sharing and fostering	Advocating for community engagement and co-creation for initiating policy

Table 3 (continued)

Project	Aim of the project	Location	Initiators	Community Tasks	Approach to Data	Science-Policy-Society Interface
	urban areas and empower communities to seek solutions.				citizen engagement through participatory data collection, analysis, and action.	change from the bottom-up.
InfluenceAir (Brussels, 2021)	To build a comprehensive sensor network to raise awareness about air quality and its health effects.	Brussels	Citizen groups	Measurement and mapping of local pollution levels	Variation and validation test performed for data. Data is mainly used for raising awareness, unsure about use for scientific research.	Creating citizen-driven air quality monitoring sensor networks. Bridging the gap between science and society.
Luftdaten (Luftdaten, 2021)	To promote environmental resilience through community-driven, open environmental data.	Multiple European cities	Volunteer urban developers, non-profit organization	Building sensors, monitoring air quality	Open data to create digital solutions for more democratic participation and open knowledge.	Initiating multi-stakeholder discussion about ambient air quality standards.
AirKit (Sense, 2021)	To develop an air quality monitoring framework that fosters open processes of research co-creation and environmental action.	UK	Academia, citizens, local governing bodies	Monitoring site selection, sensor installation, monitoring air pollution incidents	Citizen data is used for creating data stories that provide context and meaning to the data by adding observations.	Allowing citizens to communicate data to decision-makers and propose actions.

children, pregnant women, and elderly people (Landrigan et al., 2018). Most of the countries in the region suffer from poor air quality due to different reasons such as high rates of urbanization, increase in the use of motor vehicles, and industry development (Cepeda et al., 2017; Gulia et al., 2015). Mexico has seen a serious deterioration of air quality in recent years due to transport-related pollution and wildfires (Bel and Holst, 2018; Son et al., 2018). Countries like Chile experience high levels of particulate matter due to extensive use of wood for cooking and heating (Paardekooper et al., 2020; Tagle et al., 2020). One of 104 cities monitoring PM 10 and 9 of 57 cities monitoring PM2.5 meet WHO guidelines (Riojas-Rodriguez et al., 2016). Moreover, only 16 of 58 cities with more than 500,000 inhabitants report air pollution measures. 17 countries in Latin America and the Caribbean (LAC) have air quality networks, but these networks cover only 20% of the total LAC population (Riojas-Rodriguez et al., 2016). Responding to this, several Citizen Sensing projects across the region are trying to address the problem of air pollution and poor air pollution monitoring (Valencia and Fonseca, 2019). Table 4 summarizes some of the major CS initiatives across different regions in Latin America. Most of the initiatives consist of collaborative frameworks that bring together the efforts of local, regional, and national administrations to improve air quality. In Colombia, the government-run initiative Ciudadanos Científicos aims at raising awareness about air quality while improving the information about the distribution of air pollution (Hoyos et al., 2020; SIATA, 2021). Citizen scientists do not participate in design but are involved in data collection and receive feedback from the project. Data collected is open access and it has been included in scientific studies about the effects of fireworks on particulate matter concentrations in Medellin and its Metropolitan Area (Hoyos et al., 2020). Other CS projects like CanAirIO (CanAirIO, 2021) and Unloquer (Valencia and Fonseca, 2019) are examples of bottom-up, autonomous, civil initiatives that are building citizen networks across cities in Colombia to foster multi-stakeholder partnerships and create fine-grained air quality datasets for decision making. Citizen collectives like these are already creating impact at the local levels allowing communities to initiate interactions with decision-makers (Valencia and Fonseca, 2019). CanAirIO has also participated in MeCAB, a citizen initiative that promotes air quality governance and aims at influencing Bogota's local authorities (MeCAB, 2022). Similarly, there are collaborative initiatives like Redspira (2018) in Mexico and OpenSeneca (2019) in Argentina that are using crowdsourcing methods to generate air quality data that is used by the local governments for shaping policies. Various projects, including Canario and Unloquer from Colombia and Open-Seneca from Argentina, have developed diverse channels for co-creation, such as participatory workshops for sensor design and assembly and citizen workshops for designing scenarios for pollution monitoring.

Redspira has been successful in creating collaboration agreements with the Mexicali City Council as well as the Baja California Ministry of Health for joint actions to measure and improve the air quality[6]. Similarly, OpenSeneca has been collaborating with the Ministry of Environment and Sustainable Development and the Buenos Aires city government to strengthen the collaboration for scaling the CS project across Argentina[7].

The CS projects are mainly focused on complementing traditional monitoring networks by creating citizen-sensing networks. In several aspects, they are linked to social innovation where they bring together students, maker groups, and local stakeholders to use DIY tools to create low-cost air quality sensing solutions. Although trust and acceptability of citizen-generated air quality have grown, several challenges remain, particularly the institutionalization and adoption of CS initiatives by government bodies and incorporation of the citizen-generated data into national policies.

Summary. In the section "Insights from geographical perspectives", we explored several CS projects to understand how they discuss several interlinked elements that are crucial for creating a successful CS project, namely citizen engagement, approach to data, and science–policy–society interface. While community engagement in co-creation and data collection activities is prominent in most of the projects, the actual impact on policies has been limited. Other barriers to CS include issues related to technology complexity, limited interaction among key stakeholders, and lack of appreciation from the decision-makers.

We note that the relationship between scientists, decision-makers, and citizens can be a complex one. However, CS can be considered as a way to tap into citizen experiences and knowledge that can play a significant role in improving the policy-making process (as highlighted in several projects like AirBox, CuriousNoses, Redspira, and OpenSeneca).

Discussion

As discussed in the section "Insights from geographical perspectives", CS has been widely adopted in several countries to tackle the problem of air pollution. The current CS practices are already addressing challenges related to engagement, data, trust, and reliability. However, there are some concerns related to technological barriers and official endorsement of CS as well as citizen-generated data that need to be addressed to realize the full potential of CS. None of these concerns are insurmountable; with careful planning and selection of the right methods and interventions, they can all be overcome.

In this section, we discuss how CS initiatives can benefit from using open and secure technologies that not only allow the citizens to monitor the environment but also enable them to achieve citizenship. We also discuss how integrating a well-designed CS framework with the decision-making process can facilitate widespread participation and promote trust between key stakeholders.

From data intelligence to civic intelligence. Citizen-generated data is now widely used to advance science and can potentially be applied to help shape policies. So far, this potential is not fully realized. This is probably in part due to the complexity of the technological solutions and lack of information about data and privacy, which acts as a barrier to participation in CS programs. As discussed by Turbé et al. (2019), ease of engagement remains one of the strong predictors for successfully providing policy evidence. Most of the CS projects in the area of environmental monitoring rely heavily on the advancement in the field of information and communication technology (ICT). A wide range of technological solutions is used for data collection, knowledge sharing, data visualization, analysis, and dissemination (Newman et al., 2010). CS air quality monitoring projects usually use low-cost and low-power IoT devices to gather air quality data and different statistical methods and machine learning approaches to interpret and analyze that data. Different web platforms and dashboards are created for proposing local interventions, but the technologies are generally designed for a well-informed "global user" (Pritchard and Gabrys, 2016). It is generally assumed that the person undertaking air quality monitoring is likely to have good technical knowledge about different computing technologies. However, this is not always the case. More technology-oriented solutions in CS do not always guarantee more civic engagement and better data quality. For example, the use of

Table 4 Summary of key citizen-based air quality monitoring projects in Latin America.

Project	Aim of the project	Location	Initiators	Community tasks	Approach to data	Science–policy–society interface
Redspira (2018)	To develop a system that combines citizen data and official environmental data to create a collaborative air quality monitoring network.	Mexico	Citizens	Crowdsourcing air quality data	Open data platform to share data with multiple stakeholders. Data is used for local government to support policymaking	Strengthening air pollution monitoring in Mexicali by creating citizen sensing networks to support regulatory monitoring infrastructure.
Open-Seneca (2019)	To empower citizens with air pollution data to raise awareness, promote behavioral change, and inform policymakers on environmental issues.	Argentina	Academia, research institutes, maker groups, non-profit organizations	Crowdsourcing air quality data by mounting air quality monitoring devices on bikes	Validated data is used to promote behavioral change and inform decision-makers.	Using collective intelligence to find pollution hotspots and raise awareness. Collaborating with the government to scale the CS project across the country.
Unloquer (Valencia and Fonseca, 2019)	To raise awareness about local air quality and empower citizens in making informed choices.	Colombia	Citizens	Crowdsourcing air quality data	Data is not validated before streaming. Open data platform to share data with multiple stakeholders.	Allowing the community to participate in data collection and engage in addressing local air quality problems.
Citizen Science (Ciudadanos Científicos) (Hoyos et al., 2020)	To raise awareness about local air quality and empower citizens to make data-informed decisions.	Colombia	Local government	Crowdsourcing air quality data	Real-time data is displayed online, validated data is shared with multiple stakeholders.	Allowing the community to participate in data collection and engage in local air quality problems. Supporting local governments with air quality data to support policymaking during pollution episodes.
CanAirIO (2021)	To build a citizen network that maps air pollution using low-cost sensors and promotes awareness.	Colombia	Citizens	Assembling monitoring devices, tracking air pollution episodes.	Data is not validated before streaming. Open data platform to share data with multiple stakeholders.	Creating an inclusive environment for promoting citizen participation in air pollution monitoring. Advocating for putting the topic of air quality on the local political agenda.
Aire Envigado (Metropol Colombia, n.d.)	To raise awareness about local air quality using DIY monitoring devices.	Colombia	Citizens	Setting up monitoring devices	Open data platform to share data with multiple stakeholders.	Allowing the community to participate in data collection and engage in addressing Envigado's air quality problems.

Box 2 | Understanding intelligence

There are different concepts of intelligence, which we would like to clarify in the following:

- Human intelligence: The ability to reason, think critically, adapt and learn from experience.
- Emotional intelligence: The ability to use emotional information to adjust to social contexts and master social interactions successfully.
- Artificial intelligence: The ability of machines to simulate aspects of human intelligence and perform human-like actions based on Big Data and Machine Learning approaches.
- Collective intelligence: The ability to jointly generate solutions that are better than individual solutions. (When applied to animals, one often speaks of Swarm Intelligence.)
- Civic intelligence: The ability of people to collaborate and work collectively towards addressing civic goals. This typically involves collective intelligence.
- Hybrid/Synergistic Intelligence: The ability to augment intelligence by creating symbiotic interactions between humans and machines.

Civic Intelligence obviously builds on Human Intelligence, but considers cooperative and social aspects, and makes use of Emotional Intelligence, too. As the concept of 'Hybrid' or 'Synergistic Intelligence' shows, it may be supported and extended by the use of Artificial Intelligence.

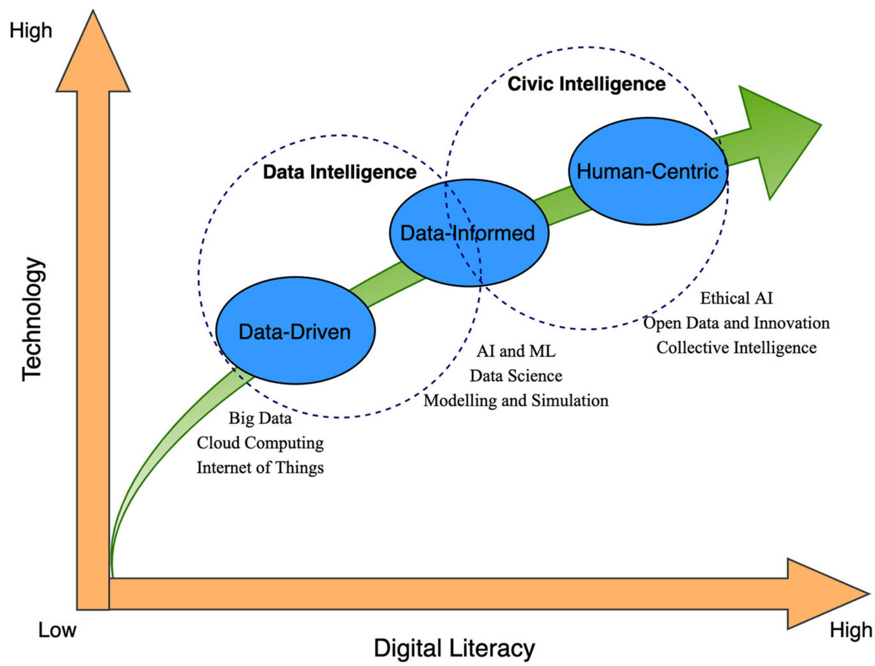

Fig. 3 Understanding how human-centric solutions can promote civic intelligence. Digital literacy and citizen engagement can be improved by using open-source and ethical technological frameworks.

machine learning algorithms and advanced artificial intelligence (AI) tools can improve data management and interpretation, but these algorithms are often black boxes. It is important to look for solutions that are explainable, interpretable, and transparent (Franzen et al., 2021). The definition of different types of intelligence is outlined in Box 2. It is clear that there is a need for a synergy between AI and civic intelligence that allows people to make better decisions and helps them to reach collective intelligence at scale. High-level technological solutions can promote data intelligence, but for promoting collective intelligence more human-centric solutions must be developed and used. In Fig. 3, we show how human-centric technological solutions can promote "civic intelligence", thereby promoting the efficient use of technology and enhancing digital literacy. Attention must be given to implementing open-source solutions that are ethical and safeguard human rights (Helbing et al., 2021; Pournaras et al., 2017). As citizen scientists are mostly volunteers who are willing to contribute to science and society by giving their time and data, it should be a priority to use ethical technological frameworks that promote digital democracy and safeguard personal data. Not only would it build trust between citizen scientists and other stakeholders, but it would also promote meaningful engagement and data collection.

Co-creating evidence to help shape better policy. The process of policymaking is an adaptive multi-step process that includes problem identification, policy formulation, adoption, implementation, and evaluation. Policy formulation is one of the key steps of the policymaking process and it involves collecting and using evidence. Policymakers tend to interpret evidence as either scientific evidence or non-scientific evidence (Lomas, 2005). Although citizen-generated data presents unprecedented opportunities to increase knowledge sharing, collaboration, and data democratization; recognition of such data as legitimate scientific evidence remains an issue (Burgess et al., 2017). To address this challenge and find effective ways of using citizen-generated data

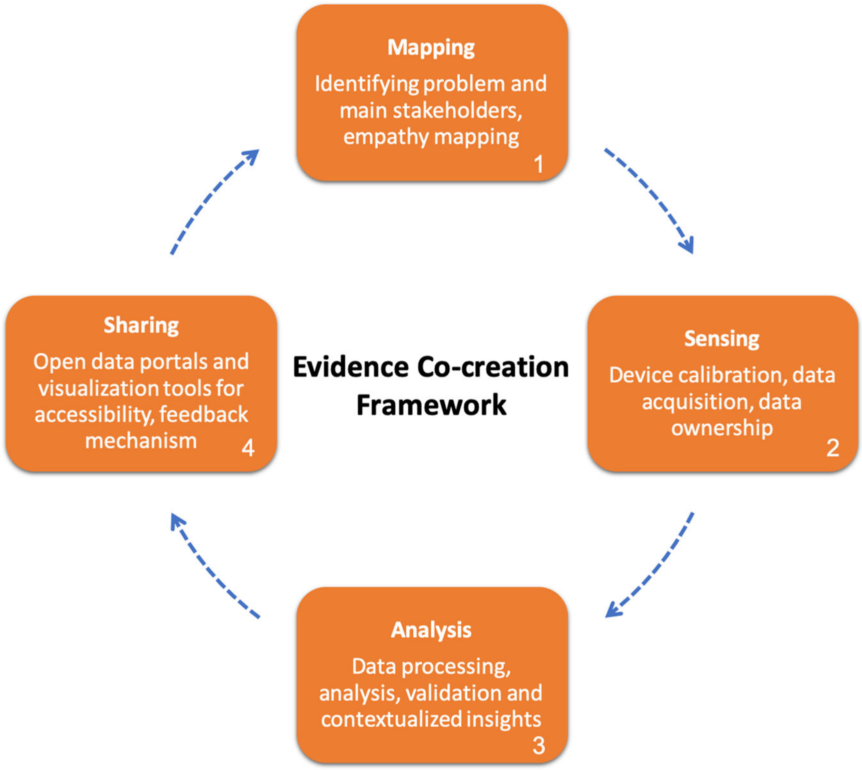

Fig. 4 Evidence co-creation framework. The proposed framework is an iterative process for creating evidence using citizen-generated data.

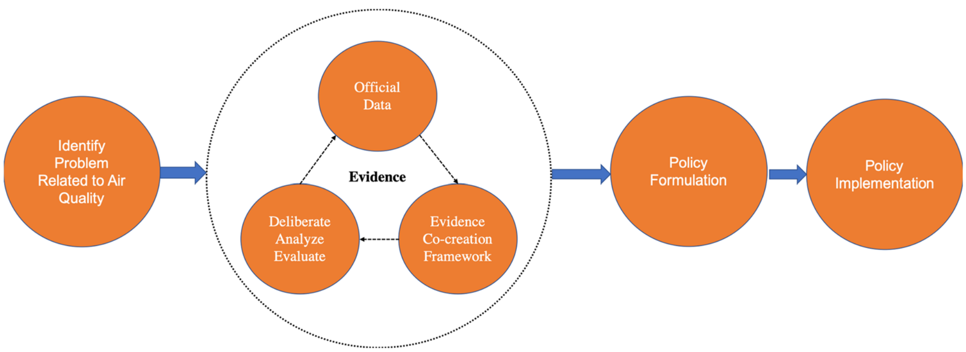

Fig. 5 Integration of the ECF within the policy-making process. Citizen-generated data obtained from the ECF is merged with official data to form the new evidence, which is then discussed, analyzed, and evaluated before policy formulation.

as evidence for policy purposes, we have proposed the Evidence Co-creation Framework (ECF). Figure 4 shows the ECF which is an iterative process for creating evidence using citizen-generated data. It has several interconnected components.

Mapping. This step identifies the problem and key stakeholders. The empathy mapping exercise is used to involve everyone and gain insights into the target group. The exercise leverages behavioral insights that are likely to improve the policy formulation process as it allows the decision-makers to prioritize problems based on the opinion of the citizens.

Sensing. This step allows the key stakeholders to co-define data standards and co-design data collection campaigns. Ethical issues related to informed consent and data ownership are discussed. Citizens are made aware of necessary protocols of confidentiality and anonymity that are followed as part of the process of data collection and curation.

Analysis. This step includes data processing and analysis using scientific standards. Data is checked for outliers and necessary steps are followed for creating a usable dataset. It is followed by data validation where the data is checked for reliability by comparing it with standards set by regulatory bodies.

Sharing. Sharing is particularly a key step of the ECF. The process of data sensing and analysis often results in large datasets that are not easy to interpret. It is imperative to translate and communicate the data in a way that is easier for everyone to understand. Interactive visualizations and digital tools can be used to share the evidence and receive feedback from multiple stakeholders. The feedback mechanism is also valuable as it allows stakeholders to critically analyze the framework and the outputs, and provide suggestions for improvement.

The ECF is then integrated within the policy-making process, as illustrated in Fig. 5. It complements the official data that is used as evidence before formulating a policy. The official data is combined with the data obtained from the ECF followed by deliberation, analysis, and evaluation. This includes discussion and debate over the evidence and evaluation, to check if the evidence meets the scientific standards. This step can include several iterations before the official formulation is done. Integrating citizen data within policymaking is a complex process and it is not possible to comment on the impact our methodology would have, as in most of the countries, issues related to air quality and citizen involvement are politically charged. Nevertheless, combining participation, multiple stakeholder deliberation, and scientific analysis has shown positive results in other challenging areas, like water sustainability (Garrick et al., 2017). Engaging people with the policy process could have a significant impact as it would make policies more understandable and acceptable.

Conclusion

CS coupled with participatory sensing has created a new paradigm of civic intelligence where communities engage in collaborative ways to monitor their surroundings. As compared to the conventional methods in which the interactions with communities and decision-makers are limited, citizen sensing has emerged as a useful tool that can bridge the gap between people and policymakers by opening up possibilities of co-creation and collective decision-making. The use of CS in air quality monitoring is growing, and so too is the quality of the data. But, such data so far is seldom used for policymaking. The main reason for this is the lack of a clear methodology to translate citizen-generated data into evidence that can be used by policymakers in decision-making.

This review examined how key CS air quality monitoring initiatives across Asia, Africa, Europe, and Latin America are opening up spaces for interaction between community members and decision-makers. Through a comparison of different CS projects and the methods used by them, this review sheds light on how these projects are generating evidence that has the potential to influence air quality governance. It was observed that most of the projects significantly focused on generating scientifically valid data that could complement the traditional air quality monitoring networks while a limited number of the projects showed visible policy impact. Furthermore, the review of CS projects revealed some key barriers, including technology complexity, limited interaction between key stakeholders, and the lack of appreciation from decision-makers. To address this, we have discussed how reducing technological complexity and promoting the efficient use of technology can promote meaningful engagement, build trust between key stakeholders, and promote collective intelligence. We have also proposed the ECF, which is an iterative process for creating evidence using citizen-generated data. The ECF aims to create an open and transparent process that helps in evidence co-creation and fosters multiple stakeholder partnerships. It allows data collection activities to be designed in cooperation with the communities to have a bigger socio-political impact.

Even though we have addressed issues related to air quality, our approach can theoretically be applied to other CS practices that leverage citizen-generated data. As we highlight in this review, transparency, openness, and active community participation could potentially remove the barriers between society, science, and policy. It could add credibility and legitimacy to the evidence used for making policy decisions making it more acceptable among a wider array of key stakeholders.

We performed a comprehensive search of literature that addresses the issue of air quality, CS, and policymaking. One limitation of this study may be that some of the references could have been omitted because they were not indexed in the WoS database. To perform a detailed review, we did not restrict our search to academic publications; rather, we investigated several grassroots and collaborative projects that don't appear in the literature but have well-documented online resources. Although the number of such projects is limited, these projects provide valuable insights that can be used by researchers and practitioners to develop future CS initiatives to address the issue of air pollution.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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Notes

1 https://www.webofscience.com/wos/woscc/basic-search
2 AND retrieves all documents that contain both the terms. * is a search function that looks for words with multiple endings. Example: "Policy*" will look for words like policy making, policy analysis, etc.
3 For analysis, the *bibliometrix* package in R was used (Aria and Cuccurullo, 2017).
4 https://www.government.nl/topics/active-citizens/citizen-participation
5 https://www.eufje.org/images/docConf/visio2020/REPORT_BELGIUM.pdf
6 https://www.redspira.org/index.php/vinculacion
7 https://acceleratorlabs.undp.org/content/acceleratorlabs/en/home/our-work/Climate-change-air-pollution-UNDP-COP26-Climate-Promise-Environment-Green-Renewable-Sustainability-SDGs.html

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The authors declare no competing interests.

Ethical approval
Not applicable as this study did not involve human participants.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

Additional information
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